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River Diversions and Shoaling

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note describes the current knowledge of the potential impacts of river diversions on channel morphology, especially induced sedimentation in the river channel. Processes considered in this note are those most pertinent to riverine, as opposed to estuarine, aspects of diversions. In particular, this note provides general guidance on the physical process issues, outlines strategies for more effective application of existing tools, and summarizes the needs for developing better tools to address the issues. These issues become critical in the planning and design of diversions when the operation of these structures could adversely impact other authorized uses of the river.

For example, the management of water and sediment resources in coastal Louisiana for the mitigation of land and habitat loss must be balanced with the needs for flood control and navigation. In one management scenario, plans are being formulated (U.S. Army Corps of Engineers (USACE) 2004) to divert flow from the Mississippi River to distribute water and sediment as a way of rebuilding marsh areas and sustaining existing wetlands. One concern with this management option is the potential impact these diversions will have on deposition in the navigation channel and the potential for increased maintenance dredging.

One of the main obstacles in developing a consensus and an optimum strategy for balancing these needs is the lack of efficient tools and general guidance for evaluating the impacts of diversions on navigation and flood control and, conversely, the impact of navigation and flood control measures on the distribution of the resources to the wetland ecosystem. Impacts are potentially created over a wide range of space and time scales, which the impact assessment approach and tools must consider. For example, the long-term impacts within the river channel are influenced by the long-term response within the distributary area for the diversion.

This note will conclude that a successful balancing of the needs of restoration and wetlands management with the needs of navigation and flood control, particularly through Mississippi River diversions, will require the following:

1. A detailed geomorphic assessment, guided by
2. Conceptual model(s) of the river, receiving basin and their interactions, to provide understanding of the underlying processes.
3. Both of these (1 and 2 above) will guide the development and use of physics-based tools and models for exploring the consequences of activities in and around the river.

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BACKGROUND: River diversions are used in many parts of the world to divert water and sediment for purposes such as flood control, irrigation, hydropower, municipal water supply, and environmental enhancement and/or restoration. Temporary diversions constructed to divert a stream while other construction activities are ongoing within the channel are normally closely monitored and can provide valuable data. However, these diversions are not necessarily representative of long-term impacts that could affect navigation or flood control. Permanent diversions, including those that operate on variable time schedules, are the primary subject of this technical note.

Problems of land loss in coastal Louisiana have been extensively documented (Gagliano 1981; Britsch and Dunbar 1993; Boesch et al. 1994; Day et al. 2000). The primary approach to providing much-needed water and sediment to the marsh areas is through diversions from the Mississippi River. Diversions from the main stem of the lower Mississippi River are either controlled by some engineered structure (for example, the Caernarvon Diversion) or are essentially uncontrolled (for example, the West Bay Diversion). Engineering experience lies primarily with controlled diversions, which provide explicit control over the water and sediment delivery. Uncontrolled diversions, however, must be carefully considered and designed so that the diversion does not grow naturally beyond its desired capacity and is capable of delivering the expected resources.

The evaluation of long-term effects of a river diversion project requires estimation of the long-term geomorphology of both the river channel and the receiving basin for the diversion. The time period of the assessment of impacts will influence the spatial domain required for the geomorphological analysis. The initial flow and sediment diversion capacity will change with time as the hydraulic efficiency of the flow pathways within the receiving basin changes due to the geomorphological evolution. Changes in the river bed associated with modified long-term sediment transport capacity may affect the stage-discharge relationship at the diversion site. These processes are conceptually the same as those which drive large-scale regional delta lobe switching of the full Mississippi River delta over geologic time scales.

In the assessment of impacts of diversions on a larger spatial scale, the long-term changes in the local friction must be considered. For example, the succession of various vegetation types on both accreting and eroding wetlands should be considered due to their influence on flow capacity and flow distribution within the overall system (Day et al. 2000). In addition, the basic concept of the growth and decay cycle of the receiving wetland must be considered as a balance among the sediment supply, sub-delta wetland basin area, and local subsidence rates (Roberts 1997). The temporal scale for the benefits from the local sediment deposits within the wetlands will be a function of the sediment supply itself. In addition, a more natural pulsing of the river water and sediment supply has been recognized as important to the sustainability of the local wetland receiving the diversion resources (Day et al. 1995). Some attempts have been made to model the time evolution of the ecology of Louisiana wetlands (White et al. 1997; Martin et al. 2002). If a comprehensive system-wide analysis of river diversions is undertaken, the landscape changes over the duration of the analysis should also be considered (Martin et al. 2002).

The potential for changes in the geomorphology downstream of a diversion raises concerns over the impact on navigation channel stability, maintenance and, therefore, safety. The location of the natural thalweg of the river is taken into consideration when laying out the navigation

channel. Changes in morphology can have a dramatic impact on the maintenance of a channel by trying to maintain an alignment that is no longer optimum.

The impacts of a single small-scale diversion may have a minimal effect on the system. However, the impact of a large diversion or the cumulative effects of a number of small diversions can become significant. Morphological responses are normally associated with thresholds for sediment mobility, and responses can be highly nonlinear. A comprehensive strategy for evaluation of these effects is needed.

PROCESSES: An engineering evaluation of proposed diversions begins by identifying the processes critical to the hydrodynamics and sediment transport within the overall system. An accurate conceptual model of the processes is important to anticipate potential impacts and help identify the appropriate tools to study the problem. In addition, it is necessary to consider the impacts of diversions on a variety of scales. If the goal is to manage the performance of a number of diversions and their interactions, then the minimum scale logically should be proportional to the distance between the diversions. If diversions all along the river are being considered, it becomes clear that a larger scale evaluation is required. A large-scale conceptual model of the Mississippi River system covering the full domain of all proposed diversions is a starting point. Such a conceptual model (or models) would inform and benefit from the geomorphic assessment mentioned earlier. Converting that conceptual model to an analysis strategy will then facilitate evaluation of cumulative effects from multiple diversions.

In its simplest form, the conceptual model for assessment of sediment transport capacity is through the concept of stream power as proposed by Bagnold (1966). Stream power is defined as the time rate ability of the flow within a channel to do work, that work being the energy available to transport sediment. The rate at which this available energy can do the work of moving the fluid, the cross-sectional total stream power, Ω , is expressed as the product of the specific weight of the fluid, γ , the water discharge, Q , and the energy slope, S , which may be approximated by the slope of the channel bed:

$$\Omega = \gamma Q S \quad (1)$$

As can be seen from this equation, any change in the magnitude of flow, due to a single diversion for example, has a direct impact on stream power. In the case of river diversions, as flow is diverted from the main channel, the stream power of the main channel is reduced, resulting in a reduction in the ability of the flow to do work at a given rate; i.e., a reduction in the ability of the main channel flow to transport sediment.

The next level of conceptual model for consideration of a single diversion is through any basic total-load sediment transport equation. If the equilibrium total sediment load is the product of the water discharge and the equilibrium mean sediment concentration associated with that total transport capacity, and that concentration is assumed proportional to the water discharge raised to some power, we get

$$Q_{se} = Q_w C_e \quad \text{and} \quad C_e \approx A Q_w^\alpha \quad \text{then} \quad Q_{se} \approx A Q_w^{(1+\alpha)} \quad (2)$$

where Q_{se} , Q_w , and C_e are the equilibrium sediment flux (total sediment load), water flux, and equilibrium mean sediment concentration upstream of the diversion, respectively; α is the coefficient on the concentration dependence; and A is a constant. The equilibrium sediment flux is thus proportional to the water flux to a power of $(1 + \alpha)$. If some fraction, β , of the water flow is diverted from the main stem (Figure 1), then the new equilibrium sediment flux downstream of the diversion in the main stem will be $Q_{sde} = Q_{wd}C_{de}$, where Q_{wd} and C_{de} are, respectively, the water flux and the new equilibrium mean sediment concentration downstream of the diversion. The equilibrium concentration downstream of the diversion will then be $C_{de} \approx A Q_{wd}^\alpha = A(1 - \beta)^\alpha Q_w^\alpha$. Therefore, the ratio of the equilibrium concentration downstream to equilibrium concentration upstream is

$$\frac{C_{de}}{C_e} = (1 - \beta)^\alpha \quad (3)$$

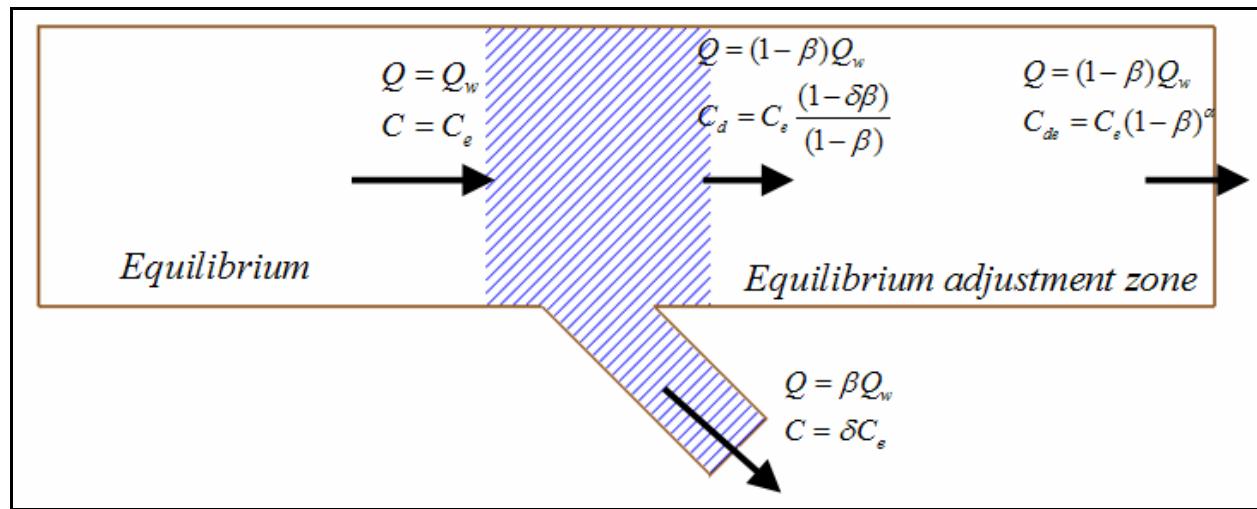


Figure 1. Flow diversion macroscale flux balances

Since the fraction of flow diverted is less than 1 and the coefficient α should always be a positive number, we always have $(1 - \beta)^\alpha < 1$. The equilibrium mean concentration downstream of the diversion is thus less than the equilibrium mean concentration upstream of the diversion and is independent of the sediment concentration of the diverted water and is only a function of the water discharge. If the sediment concentration passing immediately downstream of the diversion is unchanged, there will be an adjustment zone in the main stem of the river over which sediment will deposit from the flow until the new lower equilibrium concentration is reached.

As flows move toward the diversion, it is reasonable to assume that the concentration upstream of the diversion has reached equilibrium. If we assume that there is no adjusting bed exchange in the local vicinity of the diversion (shaded region of Figure 1), the concentration in the main stem of the river immediately downstream of the diversion, C_d , can be assumed to be the remaining balance of suspended sediment left after the diversion of suspended sediment. If the diversion is designed to take a fraction, δ , of the upstream concentration, the concentration immediately

downstream of the diversion, C_d (based on the sediment balance with no bed adjustment), will be $C_e(1-\delta\beta)/(1-\beta)$. If the diversion sediment fraction is 1.0, we would have

$$\frac{C_d}{C_{de}} = \frac{C_e}{C_{de}} = (1-\beta)^{-\alpha} > 1 \quad (4)$$

So, unless the diversion is designed to take a disproportionate fraction of the sediment with the diverted water, there will be deposition downstream of the diversion. The required fraction of sediment diverted in order to keep the sediment concentration downstream of the diversion in equilibrium can be estimated by equating C_d with C_{de} .

$$C_d = C_{de} \Rightarrow C_e \frac{(1-\delta\beta)}{(1-\beta)} = C_e (1-\beta)^\alpha \Rightarrow \delta = \frac{1}{\beta} \left[1 - (1-\beta)^{\alpha+1} \right] \quad (5)$$

The differential rate of deposition, ΔD , in the adjustment zone can be estimated as the differential sediment flux at the ends of the adjustment zone

$$\Delta D = Q_w (1-\beta) C_e \left[\frac{(1-\delta\beta)}{(1-\beta)} - (1-\beta)^\alpha \right] \quad (6)$$

As an example, for a discharge of 15,000 m³/s (530,000 cfs), an equilibrium upstream concentration of 0.300 kg/m³, a diversion fraction $\beta = 0.1$, a sediment diversion factor $\delta = 1.5$, and a value of $\alpha = 1.0$, the differential deposition rate in the adjustment zone would be 3.15×10^6 m³ (4.12×10^6 cu yd) per year (assuming a bed bulk density of 1,800 kg/m³). If the sediment fraction in the diversion is increased to 1.8, the differential deposition rate would be reduced to 788,000 m³/year (1,031,000 cu yd/year). At a sediment diversion fraction of 1.9, the differential deposition is essentially zero.

It is an important feature of this conceptual model to note that, if the sediment fraction is raised above the level that provides for equilibrium downstream, the response within the adjustment zone would be bed erosion. Whether erosion or deposition, the most important indication is that the bed downstream of the diversion will be out of equilibrium with the flow and there may be the potential for a complex morphological response in the real world.

This simple conceptual model of the diversion of sediment and water serves to illustrate the primary issues associated with the design of diversions, but tells nothing about where the sediment will deposit downstream. This simple model assumes that the system upstream of the diversion is in steady-state equilibrium at transport capacity, that there is no localized adjustment in the bed in the vicinity of the diversion, and that there is an adjustment zone some distance downstream of the diversion within the main stem of the river.

A detailed discussion of all the processes that are important to the successful management of diversions in a system-wide manner is beyond the scope of this technical note. Some of the major processes and parameters are listed in Table 1, sorted by a general description of the

spatial scale of concern. The regional length scale may vary from tens to hundreds of miles. The cross-sectional length scale is considered to be the controlling scale when evaluating a local reach of the river, and may vary from hundreds to thousands of feet. The processes at a local length scale are essentially those of interest over the local vertical water column and vary from feet to tens of feet.

This simple conceptual model does not address geomorphological changes that may also occur in the system. Such a simple tool does, however, serve as a check for other tools that may predict counterintuitive results.

Table 1
Modeling Technical Needs by Process

Process	Spatial Scale	Modeling resolution needed ¹			
		1D ²	2DH ³	2DV ⁴	3D ⁵
Flood routing	regional	X	x		
Sediment load	regional	X	x		
Channel bed aggradation (slope)	regional	X	x		
Channel bed degradation (slope)	regional	X	x		
Sediment sorting along channel reach	regional	X			
Sediment load variation with changing discharge	regional	X			
Velocity distribution	cross section		x		X
Secondary circulation	cross section		x		X
Sediment bar formation	cross section		x		X
Shear stress distribution	cross section		x		X
Bed load transport distribution	cross section		x		X
Flow distribution at bifurcation	cross section	x	x		X
Sediment load distribution at bifurcation	cross section				X
Sediment size distribution at bifurcation	cross section		x		X
Sediment size distribution in water column	local			x	X
Vertical flow extraction profile at diversion	local				X
Vertical sediment size/concentration extraction profile at diversion	local				X
Flocculation	local			x	X
Vertical turbulent exchange/mixing	local			x	X
Sediment deposition/erosion for dredging analysis	local		x		X

¹ X is recommended; x is feasible.

² 1D = one-dimensional.

³ 2DH = two-dimensional vertically averaged.

⁴ 2DV = two-dimensional laterally averaged.

⁵ 3D = three-dimensional.

GEOMORPHOLOGICAL CONSIDERATIONS: Major design considerations for diversion channels as proposed by Nunnally (1985) include 1) determining if the channel should convey partial or all flows, 2) design of appropriate controls, 3) sizing of the channel to convey the design discharge, and 4) design to reduce maintenance. Design discharge includes both water and sediment. Additionally, it is essential to consider potential morphologic effects on both the main channel as well as the receiving channel (Watson et al. 1999). Schumm (1977) proposed that channel morphology reflects the influence of a complex series of independent variables, but the discharge of water and sediment integrates most of these, and it is the nature and quantity of sediment and water moving through channels that largely determine the morphology of stable alluvial channels. Empirical relations have been developed that relate channel morphology to water and sediment discharge. Lane (1955) presented a qualitative relation, Lane's Relationship in Equation 7, which links mean water discharge, Q ; gradient (slope), S ; bed material load, Q_s ; and median sediment size, d_{50} . Lane's Balance (Figure 2) illustrates, for example, that a decrease in discharge, Q , causes the "balance" to tilt so that the indicator (white arrow) points to "aggradation," which could be brought back to "equilibrium" by, for example, an associated decrease in the bed load transport, Q_s .

$$Q \cdot S \sim Q_s \cdot d_{50} \quad (7)$$

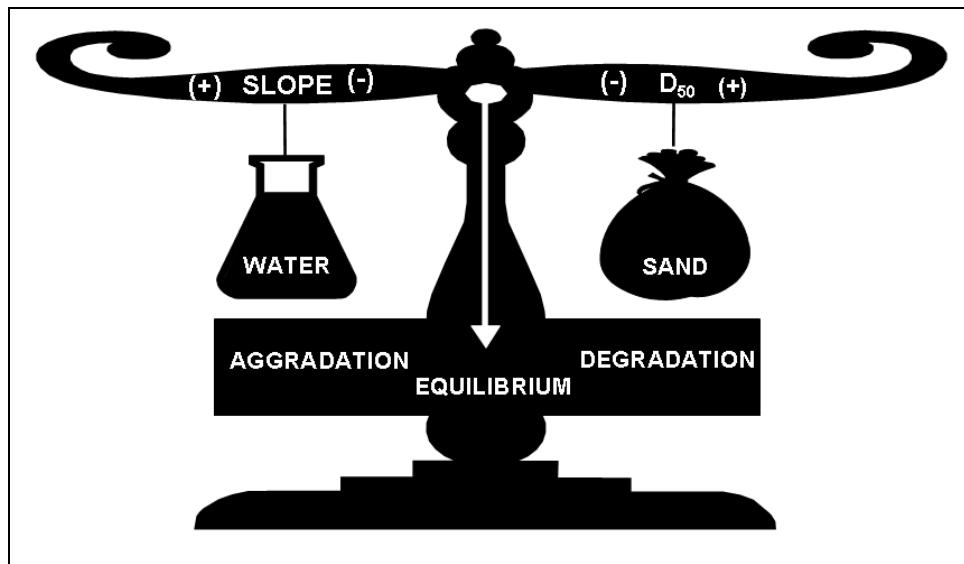


Figure 2. Lane's Balance

Lane concluded that a channel will be maintained in steady-state equilibrium when changes in sediment load and sediment size are compensated for by changes in water discharge and river gradient. Watson et al. (1999) point out that, from Lane's Relationship, it can be seen that reducing the river flow in the main channel due to a diversion, with the slope and particle size remaining constant, will result in a decrease in the sediment transport capability. Thus, aggradation could occur in the channel. If too much bed material is diverted, the sediment transport capability of the stream may increase, thus accelerating channel instability through degradation. Also, wash load from the main channel may convert to bed material load in the diversion channel, resulting in sedimentation in the diversion channel.

To address these considerations, a thorough understanding of the complex combination of the variables that impact channel morphology is required through a detailed geomorphic analysis of the system. For example, one would intuitively conclude that a small diversion would most likely have a minimal impact on a large-supply stream and a large diversion or a series of diversions could have a larger impact on the supply stream. However, a small diversion, a large diversion, or a series of diversions could all have a significant impact on the morphology of the supply stream if their impacts push the supply stream beyond a geomorphic threshold. Schumm (1977) proposed the idea of thresholds, which suggests that the response of a stream may not be proportional to the stimulus. That is, the system may respond non-linearly to a stimulus. The concept of the resilience of the system is used in assessing threshold sensitivity. Resilience is the distance a system may be from a threshold. For example, if one is ten steps from the edge of the Grand Canyon, the change incurred in taking nine steps toward the edge may not be remarkable; the tenth step may create significant change.

Two types of thresholds are characterized, termed extrinsic and intrinsic. Extrinsic is when a gradual increase in an external stress eventually produces a dramatic response in the system. An example of extrinsic thresholds is the response of sediment to an increase in the velocity and depth of flow of water over it (initiation of motion): as flow velocity increases, a point is reached when movement is initiated, or as depth of flow increases, sediment in the bed may cease to move. Schumm defines an intrinsic threshold as the result of change through time to a condition of incipient instability, without a change of external influences. A common example of an intrinsic threshold is the progressive increase in channel sinuosity and meander amplitude until a cutoff or channel avulsion results on alluvial plains and deltas. The resilience of the system to any extrinsic or intrinsic stimulus must be evaluated. It is essential that a detailed geomorphic and sediment transport analysis be conducted during the planning stage of any diversion project.

Mercer (1971) points out that one characteristic of river behavior makes the location of diversion structures very important to the control of sediment entry into the diversion channel. A strong secondary current is set up in bendways of the river whereby relatively clear water in the upper layers of the flow is diverted to the outside or concave bank and the sediment-laden lower layers of water are diverted to the inside or convex bank. The result is that a diversion structure built on the convex bank will receive a heavy load of sediment while a diversion on the concave bank will receive a much lesser load. Although this effect is pronounced, it is more observed by designers in avoiding convex banks than in building on concave banks, since designers are often more interested in diverting water than sediment. Concave banks are usually areas of active erosion, and expensive stabilizing efforts may be required. Selection must be based on prediction of how the river will behave after diversion and not how it behaves before.

With a detailed geomorphic assessment in hand and conceptual model(s) available, these and other processes can be delineated and studied in physics-based models suitable for scenario testing.

LITERATURE REVIEW: Numerous river diversions have been engineered for various purposes. While much information exists on various aspects of river diversions, the information on induced sediment deposition is limited. Often there are unintended consequences of a diversion, in large part due to the lack of tools or a strategy to address the large-scale impacts of the diversion. Some examples are summarized below:

1. An example of unintended consequences is the diversion of flows from the Santee River into the Cooper River in South Carolina. At the beginning of the last century, this diversion led to the unintended consequence of dramatically increasing the shoaling and dredging requirements far downstream in Charleston Harbor. Although this was an example of impacts of an increase in flow, the results were unintended impacts on a larger scale than the diversion. A rediversion canal was constructed in 1993 to partially mitigate the dredging requirements.
2. The diversion of the Colorado River, Texas, in 1992 near its mouth (from a direct path through the inlet to the gulf to an indirect path through Matagorda Bay) led to a dramatic increase in dredging at the mouth of the old river outlet to the Gulf of Mexico due to the reduced flushing capacity of peak riverine flood flows which now are significantly attenuated by storage in Matagorda Bay (Barcak et al. 2007). The diversion did have the intended effect of freshening the Bay and creating a new delta in Matagorda Bay. The large sediment loads in the river were made available by the dynamiting of up-river log jams in the 1930s, providing the material for a delta that cut east Matagorda Bay in half in the 1930s and, eventually, a direct outlet to the Gulf.
3. Simons and Sentürk (1976) discussed Lane's Balance as being most useful for qualitative prediction of channel response to natural or imposed changes in a river system. An example is provided which includes the construction of a diversion structure upstream of Reach A (Figure 3) to divert essentially clear water by canal to the adjacent tributary on which Reach B is located. Upstream of Reach B, the clear water diverted from the other channel plus water from the tributary is released through a hydropower plant. These investigations point out that these changes in normal river flows give rise to several complex responses in Reaches A and B on the tributary systems as well as on the main stem. They summarize that Reach A may aggrade due to the excess of sediment left in that reach when clear water is diverted. A decrease in discharge (Q^-) results in an increase in channel slope (S^+) due to aggradation:

$$Q_s \cdot d_{50} \sim Q^- \cdot S^+ \quad (8)$$

4. Copeland (1991) utilized the TABS-1 one-dimensional model to evaluate dredging alternatives in the Cubits Gap and Head of Passes reaches. The model extended along the Mississippi River from Reserve, LA (River Mile (RM) 140.8), to East Jetty, LA (RM -19.6). The Cubits Gap reach extends from RM 4.0 to RM 0.86, while the Head of Passes reach extends from RM 0.86 to RM -1.9. The study included evaluating several alternatives including over-depth dredging (advance maintenance), an in-channel sediment trap, and reduced outflow through Cubits Gap by some structural means. Cubits Gap is a distributary of the Mississippi River and, therefore, functions as an uncontrolled diversion.

The author noted that under existing conditions, sand concentrations through Cubits Gap are lower than in the Mississippi River because the bed through the gap is about 20 ft higher than in the river. Downstream from Cubits Gap there is less water in the river to carry the higher sand concentrations, and a potential for shoaling is created.

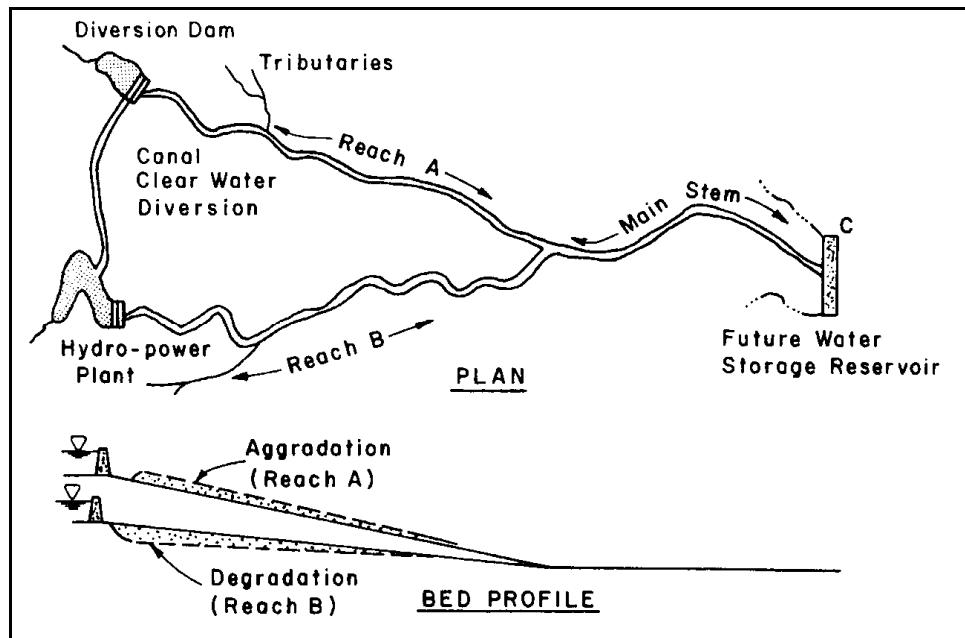


Figure 3. Clear water diversion and release (Simons and Senturk 1976)

For circumstantiation, the model was used to calculate sediment accumulation and dredging for the October 1988–May 1989 hydrograph in the vicinity of Cubits Gap and Head of Passes. In these tests, dredging to elevation -48 (-45 navigation channel elevation plus 3 ft of advanced maintenance dredging) was calculated for March and May, corresponding to active dredging periods in the prototype. Calculated quantities were not directly comparable to reported quantities because the initial bed geometry and the exact limits of dredging were unknown. The purpose of the comparison was to determine if calculated results were reasonable. The combined calculated dredging in the Cubits Gap and Head of Passes reaches was within 2 percent of reported dredging; however, calculated dredging in the vicinity of Cubits Gap was greater than reported and, in Head of Passes, was less than reported.

Flow percentages through Cubits Gap were determined from measurements. Based on these measurements, flow diversion in the numerical model at Cubits Gap and over the natural levees in the vicinity of Cubits Gap varied between 30,000 cfs (15 percent of the total river flow at Venice, LA at 200,000 cfs) and 351,000 cfs (27 percent at 1,300,000 cfs). For the Cubits Gap outflow alternative, flow redistribution quantities were uncertain at the time the model study was conducted, so an arbitrary 50-percent reduction in the discharge through Cubits Gap was assigned. The distributary sand concentration was set at 50 percent of the river sand concentration, while distributary silt and clay concentrations were set at 100 percent of the river silt and clay concentrations.

The effect of reducing flow through Cubits Gap was tested using the 1989 hydrograph. Calculated annual dredging quantities and the percent increase from existing conditions were determined. With this hydrograph, reducing flow through Cubits Gap by 50 percent resulted in a decrease in annual dredging of 5 percent in Head of Passes and 72 percent at Cubits Gap. The decrease in total annual dredging combined at Head of Passes and Cubits Gap was 1,480,000 cu yd or 25 percent.

Eleven yearly hydrographs (1974–1983 and 1989) were used to determine annual sediment accumulations. Reducing the flow through Cubits Gap provided reduced shoaling in the Cubits Gap reach for all hydrographs tested. This included both high and low runoff years. Average annual shoaling was reduced 81 percent in the Cubits Gap reach and 8 percent in the Head of Passes reach, with a combined reduction of 26 percent. The author concluded that the shoal downstream from Cubits Gap is due primarily to reduced transport potential created by the distributary. Reducing the impact of the distributary by reducing its outflow also reduces the shoaling problem downstream. In some relatively low-runoff years (1980 and 1982), the model computed an increase in annual sediment accumulation at Head of Passes with the reduced outflow through Cubits Gap alternative. This condition was created because the shoal at Cubits Gap was scoured at high flows, which caused increased sediment accumulation temporarily in Head of Passes. This condition was eventually overcome, and for years with slightly above average runoff, the increased sediment transport potential provided benefits in Head of Passes as well as in the Cubits Gap reach.

5. One of the first attempts at modeling Mississippi River diversions was made by Copeland and Thomas (1992). This effort included the development of a one-dimensional TABS-1 numerical model code between Tarbert Landing (RM 306) and East Jetty (RM -20). The model was used to evaluate long-term aggradation and degradation trends, the effect of various flow diversion schemes on dredging in Southwest Pass (SWP), the washout of a sediment sill (RM 63), and preliminary dike field schemes for Redeye Crossing (RM 224). The full model was developed in stages, with the SWP portion being used to evaluate the effect of various diversion schemes on dredging in SWP. The SWP model extended from East Jetty to Reserve (RM 140.8).

The initial scheme tested included diverting a constant 30,000 cfs away from the Mississippi River at Bonnet Carre on a year-round schedule. For this scheme, the sediment concentrations of sand were considered equal in the diversion and the river. The second scheme tested included diverting 10 percent of the Mississippi River flow at RM 6.7 with varying concentrations of sediment. The final scheme tested included diverting 70 percent (major diversions) of the Mississippi River at three diversion locations between RM 44 and RM 81. These locations were East Caernarvon (RM 81), Myrtle Grove (RM 59), and Bohemia Spillway (RM 44). Seventy percent of the flow in the Mississippi River was diverted for all discharges. For the RM 6.7 and the major diversion schemes, model runs included three sand concentrations in the diverted flow: (a) no sand diverted, (b) a sand concentration of 50 percent of that upstream of the diversion, and (c) a sand concentration of 100 percent of that upstream of the diversion. In all schemes, the silt and clay concentrations were considered equal in the river and the diversion. Also, for all schemes, an 8-year hydrograph (1975–1982) was repeated four times to simulate a 32-year record.

Model results of the diversion at Bonnet Carre indicate that the diversion would increase deposition downstream of Bonnet Carre but would have only a slight effect on dredging in SWP. The excess sediment deposits upstream of SWP and takes several years to work its way downstream. During the first 12 years of simulation, dredging requirements were slightly less with the diversion; after the 12th year, the general trend of dredging was greater with the diversion; and the total dredging required during the 32-year simulation was essentially the same with or without the diversion. Sediment deposition upstream from Head of Passes

increases by approximately 1.5 million cu yd per year for the first 12 years, and the increase levels off to less than 200,000 cu yd per year after the first 12 years.

Model results for the diversion at RM 6.7 indicate that this diversion would cause an increase in the total amount of annual dredging and deposition between 13 and 22 percent over the without-diversion scenario, depending on the concentration of sand in the diversion. This increase is primarily the result of loss of sediment transport capability because of the decrease in water discharge through SWP.

In general, the model results for the major diversion schemes indicate that the effect of diverting water and sediment will be increased deposition and dredging downstream because the reduced discharge will not be able to maintain the existing sediment concentration (see Equation 4 and related discussion). Significant increase in net dredging was seen in the river immediately downstream from the diversions where most of the sediment deposited. These increases varied depending on the diversion's location and assumed sand concentration. The results further show that the effect of the diversion site is not as significant as sand concentration on annual dredging. Furthermore, because the river would tend to narrow and fill, the diversion schemes would create significant changes to the river regime downstream. In SWP proper, the model indicated that dredging and deposition would be decreased due to shoaling north of SWP but south of the diversion.

6. Barbe et al. (2000) used the one-dimensional numerical model code HEC-6 to study how freshwater diversions along the lower Mississippi River affect sedimentation patterns in the main channel of the River. The study area included the Mississippi River from Tarbert Landing, Mississippi, to the Gulf of Mexico by way of SWP (326 river miles). This study assessed the impacts of existing and proposed freshwater diversions for two Mississippi River navigation channel alternatives, 45-ft and 55-ft draft scenarios. The existing diversions included Bonnet Carre (RM 128) and Davis Pond (RM 118). The proposed diversions included Fort Jackson (RM 19), Myrtle Grove (RM 58.7), and the Bohemia spillway (RM 36–40). For these five diversions, 10 alternatives were developed, including various combinations of diversions. For eight of the alternatives, the concentration of the sand in the diverted water was set at 50% of the concentration in the Mississippi River. For one alternative, the concentration was set equal to the concentration of the Mississippi River, and for another alternative, no sand was diverted. For all alternative model runs, the concentration of silts and clays exiting through the diversions was set equal to the concentration in the Mississippi River. A 16-year hydrograph (1978–1993) was selected because it was considered to be representative of future conditions. The hydrograph was repeated six times (96 years) to identify long-term trends.

Results from the model are presented as (a) annual dredging differences in SWP in cubic yards and (b) deposition amounts in cubic yards from the Head of SWP dredging up to the diversion site. The authors explain the results in this way. First, water and sediment exit the river via the diversion. Along with the decrease in principal riverine flow, a reduction in transport capacity occurs, causing deposition downstream of the diversion site as the cross sections adjust to conform to the reduced flow. Decreased sediment load in the river downstream of the diversion and increased deposition downstream of the diversion site cause a decrease in the amount of sediment reaching SWP. Therefore, the amount of dredging

required in SWP decreases. After some time, the channel downstream of the diversion becomes more efficient at transporting sediment, and the initial decrease in dredging in Southwest Pass will reach its maximum amount. After this, the dredging decrease tends to become smaller and, usually, an increase in dredging occurs. Essentially, the reach from the head of dredging at SWP up to the diversion site reaches an equilibrium condition. At this point, the reach has conformed to the reduction in flow. This adjustment can raise water surface elevations and affect navigation.

7. Winer and Raphelt (2005) used the three-dimensional hydrodynamic and sediment transport numerical model CH3D-SED to study the effects of major diversions of Mississippi River flow to supply sediment for creation of marshlands. This work was a continuation of a modeling effort of the West Bay Diversion (RM 4.7, West Bank) performed earlier by Gessler and Pourtaheri (2000), but instead concentrated on the Benny's Bay Diversion. A series of five upstream flows (410,000, 640,000, 780,000, 900,000, and 1,300,000 cfs) were integrated with a flow duration curve to develop a base annual sedimentation condition. These five flows were run for the existing condition (only West Bay Diversion open; no flow diverted at Benny's Bay). Analysis of the West Bay Diversion actual shoaling (Miller 2004) showed an increase in the sediment deposition extending several miles downstream of the diversion. Analysis of the numerical modeling showed similar results—an increase in deposition from West Bay Diversion (RM 4.7) downstream to RM 1.5. From RM 1.5 to RM 0 at Head of Passes, the model results showed a small reduction in sediment deposition. This decrease in sediment deposition in the RM 1.5–0 reach can be attributed to sediment deposition between RM 4.7 and RM 1.5 and the reduction of flow because of the West Bay diversion. The five flow conditions were run for the with-project conditions (assuming 50,000 cfs diverted at Benny's Bay (RM 7.5, East Bank)). Analysis of the results shows an increase in shoaling rates just downstream of the Benny's Bay Diversion. Because of the increased shoaling near the Benny's Bay Diversion, less shoaling occurs downstream in the area between the Cubits Gap (RM 3.2) and the Head of Passes (RM 0).
8. Willson et al. (2007) reviewed the capabilities and limitations of the existing Small-Scale Physical Model (SSPM), located on the campus of the Louisiana State University in Baton Rouge, LA, and two widely used two-dimensional numerical model codes (RMA2 and ADCIRC). The SSPM is a distorted-scale movable-bed physical model with a 1:12,000 horizontal scale and 1:500 vertical scale. The model extends some 102.5 miles from RM 84.5 to RM -18 (end of SWP). A Base Case plus three diversion alternatives were evaluated. These included: (a) Large Diversion Alternative, (b) Multiple Diversion Alternative, and (c) Eastern Slack-Water Navigation Alternative. The Base Case alternative included a 100-year simulation without any diversions. The Large Diversion alternative included one large (500,000 cfs) diversion and two smaller (~250,000 cfs each) diversions open for 100 years. The Multiple Diversion alternative included seven smaller (~200,000 cfs) diversions opened over a period of 28 years with a total simulation time of 100 years. The Eastern Slack-Water Alternative included a new navigation route, controlled by a sail-through lock chamber, opened on the east bank and two small diversions opened on the west bank to reduce the head on the lock and divert some sediment into the wetlands. The authors point out two main advantages of using the SSPM. First, the physical model allows for the visualization of sedimentation processes along the Mississippi River, which enhances the general understanding of project impacts. Second, due to the model sedimentation time scale, the

model can reproduce relatively long-term sedimentation processes within a few hours of testing time (50 years of sedimentation processes in 25 hr of testing).

The results of the SSPM runs show a significant increase in sediment deposition in the wetlands, significant decrease in required dredging for the Large Diversion Alternative, and minor decrease in dredging for the Multiple Diversion Alternative. The authors state that the SSPM can be used to qualitatively, and semi-quantitatively, examine sediment deposition as a result of large-scale diversions. Willson et al. (2007) also state that limitations due to the geometric scaling and distortion limit the insight and conclusions that can be reached, and so have complemented their physical modeling work with numerical modeling.

In summary, available literature shows that diverting river flows can have an impact on downstream sediment deposition rates and dredging volumes at unanticipated space and time scales. Changes in flow conditions have been documented to have the potential for a significant geomorphological response. The majority of numerical modeling studies show that flow diversions cause a depositional response in the river downstream of the diversion, particularly in the reach immediately downstream of the diversion. The impact on dredging requirements can be an immediate increase or can be a temporary decrease, with increased dredging as the long-term geomorphological response evolves. All of these modeling results are consistent with the simple conceptual analytical development discussed in the Processes section of this tech note. The small-scale physical model results, however, are not consistent with either the conceptual model or the numerical model studies. All available models (physical and one-, two-, and three-dimensional numerical models) have their uses and limitations. The consensus from most investigators is that there is a need for a comprehensive strategy for evaluation of diversions on a large scale that can address the interactions between alternative diversions and evaluate cumulative impacts (Barbe et al. 2000; Winer and Raphelt 2005; Meselhe et al. 2006; Willson et al. 2007). Given the wide range of spatial and temporal scales of potential system responses to diversions, it is obvious that the strategy will require the use of a range of tools, of varying degrees of complexity and resolution.

ANALYSIS TOOLS: The available numerical analysis tools can be subdivided into general categories by the dimensional formulation of the model: one-dimensional (1D), two-dimensional depth-averaged (2DH) (the plan, or horizontal perspective, is taken); two-dimensional laterally averaged (2DV) (the elevation, or vertical perspective, is taken); or three-dimensional (3D). A wide variety of numerical model codes are available for developing tools and performing analyses in each of the dimensional formulations. A detailed description of any of these model codes is beyond the scope of this technical note.

However, the formulation needed to address the processes of interest in studying diversions will be discussed generally. Table 1 indicates the level of formulation currently available for the evaluation of each of the processes listed. The time scales of interest for each of the spatial scales are comparable: the large regional space scales require a very long time scale to address the issue, and the very small local scales require a very short time scale to resolve the physics. The range of spatial scales delineated in Table 1 varies over a factor of a million. The temporal scales of interest will also vary over the same range, from minutes for the local parameters in the water column to decades for regional geomorphology.

The constraints placed on the analysis strategy by this range of time and space scales dictate that the regional analysis be performed at the 1D spatial level of formulation. However, integrating the processes accurately requires that, at the local scale of analysis, the temporal fidelity be resolved at the shorter time scales. The regional analysis is then relied upon to capture the long-term impacts by carefully designed model interactions. The recommended modeling formulation for each of the processes is highlighted by the bold X in the table. Constraints on the use of multi-dimensional model codes for regional analyses, however, become weaker as high-performance computing software and hardware advance.

The engineering community has any number of viable computer models that could be effectively used in the strategy of evaluating impacts of diversions. Many of these models have been used effectively around the world to evaluate various hydrodynamic and sediment transport issues. However, a survey of every available model is not practical and is beyond the scope of this effort. Therefore, the options of numerical models and other tools available for analysis will be illustrated with model codes and tools developed or maintained, and supported, by the USACE.

Sediment Impact Assessment Methods (SIAM) Computational Tool: Mooney (2007) suggests that existing techniques for evaluating sediment movement at scales larger than individual reaches should include 1) qualitative geomorphic evaluations that describe the processes and interactions, 2) sediment budget analyses, and 3) mobile boundary numerical models. Until recently, an easy-to-use sediment budget tool was not available leaving a gap in analysis capabilities between the qualitative assessment techniques and mobile boundary numerical models. Development of the SIAM tool has filled that gap.

SIAM is a 1D, reach-based sediment-continuity computational tool that provides a means for conducting rapid assessments of sediment balance in water resources projects. SIAM provides the framework for combining hydrologic, hydraulic, and morphologic information for a series of reaches representing a channel network, and computes reach average sediment transport capacity by grain size. Sediment transport capacity is balanced with sediment supply for each reach to determine sediment continuity. The SIAM computational tool has been incorporated into the Hydrologic Engineering Center River Analysis System (HEC-RAS), Beta Version 4.0, and is part of the Hydraulic Design Functions toolset. The primary application of the SIAM tool is for screening purposes during the feasibility level of study. The SIAM tool facilitates rapid assessment of multiple alternatives with regard to potential impact on sediment continuity from a system-wide perspective. Computed results are representative of a given set of channel conditions. That is, the sediment and flow are not dynamically coupled to the channel geometry (USACE 2007b).

HEC-RAS with Sediment (Beta Version 4.0): Replacing HEC-6 Scour and Deposition in Rivers and Reservoirs (USACE 1991), HEC-RAS with Sediment is a 1D movable boundary open channel flow numerical model designed to simulate and predict changes in river profiles resulting from scour and/or deposition over moderate time periods. Based upon flow records, a water surface profile is calculated that provides an energy slope, velocity, and depth at each cross section. These predictions are used to estimate potential sediment transport rates at each cross section, which are considered with volume of flow and sediment yield from upstream sources to determine the scour and deposition. Changes in bed elevation, which impact channel geometry and subsequent sediment transport potential, are also computed for each cross section.

HEC-RAS with Sediment is designed to simulate long-term trends of scour and/or deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and/or stage, or from modifying the channel geometry. The strengths of the HEC-RAS with Sediment model are that it simulates the sediment passing through each cross section and the volume of sediment deposited or scoured at each cross section. It can be used for simulating changing sediment and hydraulic conditions and for the simulation and design of channel or reservoir dredging.

TABS-MD (Multi-Dimensional): TABS-MD is a suite of models built around the 2DH models RMA2, RMA4 and SED2D. SED2D is a two-dimensional numerical model for depth-averaged transport of cohesive sediment (clay) or a representative grain size of noncohesive sediment (sand) and the deposition, erosion, and formation of bed deposits. The hydrodynamics for the SED2D model are supplied externally, usually by a numerical hydrodynamic model, such as RMA2. SED2D can be applied to clay or sand bed sediments where flow velocities can be considered two-dimensional in the horizontal plane (depth-averaged). However, TABS-MD only allows for a single representative grain size in each simulation. Separate simulations are required for sand and clay sizes.

TABS-MDS (Multi-Dimensional Sediment): The 3D code TABS-MDS, which is the USACE version of RMA10 with sediment capabilities added, couples the sediment transport, salinity, temperature, and hydrodynamics within a single code. The bathymetry is updated as sediment shoals or scours, the bed structure is accounted for, and density currents due to salinity, sediment, or temperature gradients are captured. TABS-MDS only handles multi-grain size cohesive sediments and fine material in three dimensions (not sands). Both the TABS-MD suite and TABS-MDS are based on unstructured, finite element technology with quadratic elements, allowing fine bathymetric and geometric detail to be captured only where needed, and the codes allow for two kinds of wetting and drying useful in marsh environments.

ADH (ADaptive Hydrology / Hydraulics): USACE (2007a) describes ADH as a modular, parallel, adaptive finite element model for one-, two-, and three-dimensional flow with salinity and sediment transport, and with account made for the bed structure. ADH simulates ground-water flow, internal flow, and open-channel flow. The internal flow version is a Navier-Stokes (fully three-dimensional) code that allows for accurate near-field calculations around structures as well as in pipes. The key features of the ADH model include 1) the ability to automatically refine or coarsen the mesh during simulation, resulting in more accurate solutions, and more stable, less expensive simulations, 2) the ability to run on any number of processors and machines ranging from a standard PC to the high-end supercomputer, 3) a modular style that allows additional physical processes to be added with ease, and 4) an extended continuous finite element approach that conserves mass locally without the expense of a discontinuous method. The SWWRP is funding continuing development of the code and, over the next 4 years, all of the modules within ADH will be extended to allow more capabilities. For example, eventually, an overall domain will include regions that are non-hydrostatic (Navier-Stokes), hydrostatic, and ground-water. The 2D non-cohesive sediment transport portion of the model is a beta version and is being tested. The full 2D and 3D sediment transport portion of the model is still under development with the beta version expected in 2008. Sediment libraries are being developed for use with ADH that treat cohesive, non-cohesive, and mixed sediment transport, and bed evolution and change. The libraries draw from current theories and computational techniques,

and from the SEDZLJ sediment model algorithms being advanced in the Dredging Operations and Environmental Research program. Library development also incorporates techniques from, and lessons-learned through, applications of some of the other models mentioned here, CH3D-SED, CH3D-COSED, SED2D, and TABS-MD/MDS, which are no longer actively being developed through USACE research programs but are still used and supported.

CH3D-SED (Curvilinear Hydrodynamics in Three Dimensions with Sediment): The CH3D-SED model makes computations on a curvilinear boundary-fitted plan form grid. Physical processes that are modeled, and that impact circulation and vertical mixing in a wide range of water bodies, include tides, wind, density effects (salinity, temperature, and suspended sediments), freshwater inflows, turbulence, and the effect of the earth's rotation. The boundary-fitted coordinate feature of the model in the horizontal dimension provides grid resolution enhancement necessary to adequately represent navigation channels and irregular shoreline configurations of the water body. The governing partial differential equations that are solved represent the conservation of momentum of the flow field, conservation of water volume, conservation of heat, conservation of salt, and conservation of suspended sediment, along with an equation of state relating the water density to the salinity, temperature, and suspended sediment. Sedimentation computations are based on a two-dimensional solution of the conservation of mass equation for the channel bed, i.e., the Exner equation, and the three-dimensional conservation equation for suspended sediment transport. The sediment bed is assumed to be composed of several layers, including an active layer on top. A unique feature of the mobile bed model CH3D-SED is the allocation of bed material transport as either bed load or suspended load. The sediment transport algorithms independently account for the movement of sediment as either bed load or suspended load, and also allow for the exchange of sediment between these two modes of transport (Raphelt and Alexander 2001).

There are two versions of the CH3D sediment model, one for noncohesive sediments (CH3D-SED) and one for cohesive sediments (CH3D-COSED) that is focused on fluid mud processes. The version applied to West Bay and Benny's Bay (Winer and Raphelt 2005) was the noncohesive version, which is the most appropriate for those applications. It solves for a grain size distribution and handles both bed load and suspended load.

ADCIRC (ADvanced CIRCulation): The two-dimensional, depth-integrated, finite-element barotropic time-dependent long wave, hydrodynamic circulation model ADCIRC was developed for large-scale applications within which fine detail can be specified for local areas. The ADCIRC model does not have a sediment modeling component. It is included in this list of modeling tools because of its extensive use in storm surge analysis on the Gulf coast. The impacts of diversions may need to address other project function impacts, one of which is flood control. ADCIRC serves as a method for evaluating the effects of sediment management in the coastal zone on flood control. The evolving morphology from other models could be tested in ADCIRC for impacts on the storm surge response.

ADCIRC has great flexibility in its element sizes, which is convenient for creating calculation meshes in which coarser resolution is specified in areas away from the study site to improve computation time. Resolution can be increased in areas of strong bathymetric gradients to maintain computational accuracy. ADCIRC can be applied to computational domains encompassing the deep ocean, continental shelves, coastal seas, and small-scale estuarine

systems for simulations that require months to years of time. In a single simulation, ADCIRC can provide tide and storm surge elevations and velocities corresponding to each node over a very large area encompassing regional domains such as the western North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. Features of ADCIRC include multiple forcing options, robust wetting and drying, hot start capability, calculation in spherical or Cartesian coordinates, choice of bottom-stress models, internal harmonic analysis, and user-specified global and station output. Forcing can be imposed by tidal constituents, water-surface elevation time series, flow-rate time series, wind stress, atmospheric pressure, and wave stress (Militello and Zundel 2002).

The 2DH model ADCIRC is being developed under the USACE System-Wide Water Resources Program (SWWRP) and is applied primarily as a storm surge model, solving the generalized wave equation. It is also applied as a regional tide/wind-driven circulation model to provide boundary conditions for other hydrodynamic and sediment transport/morphology change models.

Summary: Model codes and computational tools such as those mentioned above, in concert with a geomorphologic assessment and appropriate conceptual models, provide a means of exploring solutions to the issues of the Mississippi River diversions that can consider both the needs of restoration and wetlands management on the one hand and the needs of navigation and flood control on the other.

Because the scope of this note is focused on the primary physics of the water and sediment diversions, tools available for ecological or landscape modeling, or aspects related to estuarine processes, have not been reviewed. However, it is acknowledged that for a comprehensive and rigorous study to address system-wide long-term impacts of diversions, the landscape changes over time and other relevant processes should be considered, as discussed earlier.

CONCLUSIONS: The engineering evaluation of proposed diversions requires an understanding of the critical processes that impact the hydrodynamics and sediment transport within the river system. Basic conceptual models of the impacts of diversions and numerical modeling studies have pointed to the potential for diversions to impact river morphology and navigation channel maintenance. The impact of a single diversion on the morphology of the main channel may or may not be significant. A series of diversions pose a cumulative potential to have a more dramatic impact.

The first step to understanding the system is to conduct a detailed geomorphic assessment. A geomorphic assessment would provide an evaluation of the parameters that impact channel morphology and sediment transport, including the integration of these parameters.

The second step is to apply and develop, where necessary, conceptual models that inform the geomorphologic analysis, provide understanding of the underlying processes, and place both in context.

The third step is the development, validation, and use of physics-based tools and models based on hydrodynamic and sediment transport, guided and informed by the geomorphologic assessment and the conceptual model processes. The study of the impact of diversions of flow and sediment from a primary river for the purposes of redistribution of resources on the downstream reach of the primary river, for example, will require a regional-scale analysis. The

analysis should include computational tools for screening purposes and detailed design and analysis: regional, one-dimensional, models that are integrated with localized higher dimensional (3D) models at appropriate places, such as the diversion sites, and then 2DH or 3D models for the redistribution of the delivered sediment over the broader coastal wetlands.

For the largest scales of system-wide assessment, the time scale for the evaluation should be at least decades. For these longer term assessments, the deltaic growth within the receiving wetland and its feedback on flow distribution at the diversion will need to be evaluated, which should also address the landscape evolution at that time scale and consider other relevant processes.

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